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STUDYING THE EFFECT OF ALUMINUM OXIDE PARTICLE ADDITION ON THE COMPRESSION STRENGTH OF HARDENED CEMENT MORTAR

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Abstract

This study focuses on investigating the behavior of compressive strength in 21 cement mortar cylinder specimens, each measuring 76.2 mm (diameter) x 80 mm (height). To explore the impact of increasing aluminum oxide concentration on the compressive strength of hardened cement mortar, samples were prepared by using aluminum oxide material that was removed from abrasive wheels used for metal cutting. Different concentrations of aluminum oxide (1, 2, 3, 4, 5, and 10%) were used as replacements for the cement ratio as weight. The compressive strength of the cement mortar was then evaluated. Analyzing the test data revealed a decrease in the mechanical properties of the concrete samples with all levels of aluminum oxide compared to plain cement mortar without additives. This decrease in compressive strength can be attributed to the increase in cement mortar porosity resulting from higher aluminum oxide content. The most significant reduction in compressive strength occurred at an aluminum oxide concentration of 3.0%, which exhibited a decrease of about (59%). It is important to note that the aluminum oxide content in cement mortar should not exceed the permissible limit for Ordinary Portland Cement (5.3%±0.18). Hence, it can be concluded that the addition of aluminum oxide to a cement-based matrix has a negative impact on its mechanical properties, particularly its compressive strength. The importance of the research and the scope of its use lies in demonstrating the extent of the effect of increasing the percentage of aluminum oxide on the compressive strength of cement mortar.

Keywords: Portland Cement, Cement Mortar, Aluminum Oxide, Compressive Strength.

الملخص العربي

البحث يهدف الى دراسة تأثير أستبدال أوزان مختلفة من الأسمنت البورتلاندي بمسحوق أكسيد الألومنيوم على مقاومة الإنضغاط للملاط الأسمنتي. النسب الوزنية لإستبدال الأسمنت البورتلاندي كانت (1 و 2 و 3 و 4 و 5 و 10%). تم أختبار عدد 21 عينة اسطوانية الشكل بقطر 76.2 ملم وأرتفاع 80 ملم. أظهرت نتائج أختبارات مقاومة الإنضغاط على أن هناك انخفاضا لمقاومة الملاط الأسمنتي المتصلب لقوى الإنضغاط في مختلف نسب اكسيد الالمونيوم التي تم استبدالها, وكان اقصى انخفاض لمقاومة الضغط عند مقارنة بالعينة التي لم يتم فيها أستبدال الإسمنت البورتلاندي بمسحوق أكسيد الحديد 3.0% بنسبة حوالي (59%). وتخلص هذه الدراسة على أنه يجب أن لا تزيد نسبة أكسيد الألومنيوم في مسحوق الأسمنت البورتلاندي عن تلك النسبة الموصى بها من قبل المصنع وهي (5.31%), حيث أن زيادة نسبة أكسيد الألومنيوم تؤدي الى أضعاف مقاومة الملاط الأسمنتي لقوى الإنضغاط المسلطة عليها نظرا لزيادة أحتمال تكون فراغات مسامية داخل عينة الملاط الأسمنتي المتصلب. تكمن أهمية البحث ومجال الاستفادة منه في إضهار مدى تأثير زيادة نسبة أكسيد الألومنيوم على مقاومة الإنضغاط للملاط الأسمنتي.

الكلمات المفتاحية: الأسمنت البورتلاندي, الملاط الأسمنتي, أكسيد الألومنيوم, مقاومة الإنضغاط.

1. INTRODUCTION

The definition of mortar is a mixture of water, fine aggregate, and hydraulic cementitious material that has been finely divided and can be either hardened or unhardened; hydraulic mortar [1]. Bricks, stones, and concrete masonry units are joined together, the spaces between them are sealed, and mortar is used for decorating. Pitch, asphalt, and clay are additional types of mortar that are used in between bricks. As cement mortar ages and continues to cure, it gets harder. Since mortar is less expensive and quicker to repair, mortar must be weaker than building blocks [2]. The behavior of mortars built with high strength and high performance cementitious composite materials depends on

the mortar matrix's performance, despite very substantial advancements in cement and concrete technology [3].

In the past, numerous studies have been carried out to investigate the incorporation of different percentages of aluminium oxide particles in concrete composites. One such experimental study was conducted by L. Moutei in 2018, Examine how the alumina powder addition affects the cement paste's mechanical and physicochemical characteristics. Alumina powder (88 μm), Portland cement, sand, and water were combined to create the mortar. The study demonstrated that the compressive strength is enhanced by the addition of 12% alumina powder [4].

In 2013, Moustafa M. Mohammed conducted a study focusing on aluminium matrix composites reinforced with alumina particles at weight percentages of 5%, 10%, and 15%. The study employed multifactor-based experiments to investigate various aspects of these composites. The fabrication process involved utilizing mechanical mixing techniques, followed by sintering in a vacuum furnace at 600°C for 1 hour. The study aimed to assess the effects of alumina percentage on several properties, including density, microstructure, electrical and thermal conductivities, hardness, and compression strength. The results revealed that the sample containing 5% alumina achieved near-full density. Additionally, this particular sample exhibited the highest levels of hardness and compression strength [5].

In 2019, Lam Tang Van conducted a study to examine the impact of aluminium powder on the properties of lightweight aerated concrete. The objective of the research was to investigate the characteristics of aerated concrete incorporating 30% fly ash and varying amounts of aluminium powder. The properties studied included dry density, porosity, modulus of elasticity, and the strengths of the test specimens. The findings of the study indicated that as the aluminium powder content increased, the density of the aerated concrete decreased while the porosity increased. Moreover, an increase in the amount of aluminium powder resulted in a decrease in both the compressive strength, tensile strength, and modulus of elasticity of the aerated concrete samples [6]. The investigation of this newly modified aerated concrete, which combined local by-products in Vietnam, aimed to reduce the reliance on Portland cement and minimize the quantities of ash, slag TPP, and industrial waste sent to landfills. By doing so, it aimed to contribute to the future environmental friendliness of thermoelectric power plants [6].

Approximately thirty percent of the volume of masonry is consumed by cement mortar in building. The strength of mortar also affects how long-lasting and strong brickwork is. Because mortar is placed in between brick courses in masonry, it must have a high compressive strength [7]. The degradation of concrete elements exposed to aggressive sulphuric acid environments poses a significant durability challenge that impacts the performance and maintenance costs of essential civil infrastructure throughout its life cycle. Sulphuric acid present in groundwater, chemical waste, or arising from the oxidation of sulphur-containing compounds (e.g., pyrite) in backfill can corrode the concrete elements of the substructure. The impact of sulphuric acid on concrete is more detrimental compared to sulphate attack, as the attack by sulphate ions is accompanied by a dissolution effect caused by hydrogen ions [8]. The alkali-silica reaction (ASR) occurs when reactive aggregates come into contact with an adequately alkaline pore solution and a moisture level exceeding 80%. This reaction leads to the formation of expansive products, resulting in cracking and deterioration of the structures [9]. The initial stage of the alkali-silica reaction involves the reaction between hydroxyl ions (OH^-) in the pore solution and reactive silica present in the aggregate. The alkali metal cations (Na^{++}) do not directly attack the silica. The alkalis initially contribute to the high concentration of hydroxyl ions in the solution and subsequently participate in the formation of an expansive alkali-silica gel. The extent of expansion and resulting damage in concrete affected by the alkali-silica reaction depends on various parameters, including the availability of alkalis in the system, the nature and quantity of reactive silica in the aggregate, exposure conditions (such as temperature and moisture availability), and the level of internal and external constraints on movement (e.g., the amount and distribution of reinforcing steel) [10]. Inadequate compaction can also lead to the formation of pores in concrete. These pores significantly influence the most important properties of concrete, particularly its strength. Well-compacted concrete, produced with hard, low-porosity aggregates, can be considered a multiphase material comprising coarse aggregates embedded within a mortar matrix [11]. The degradation of concrete elements due to external attacks poses a significant durability issue that impacts the performance and maintenance costs of essential civil infrastructure throughout its life cycle. Inadequate compaction of concrete also contributes to this durability issue by increasing the presence of pores in the concrete members [12]. Therefore, in order to address these environmental attack problems, it is necessary to investigate the effect of increasing aluminium oxide content in concrete. It is suspected that higher aluminium oxide content may result in increased porosity and reduced performance of the concrete. The focus of the present study is to examine the structural changes in concrete when incorporating different percentages of aluminium oxide as admixtures. The objective is to incorporate aluminium oxide powder (Al_2O_3) particles into the cement mortar mix at percentages of 1.0%, 2.0%, 3.0%, 4.0%, 5.0%, and 10.0%. The mechanical properties of the cement mortar, considering the partial replacement of (Al_2O_3) particles in the concrete paste, were measured as part of this study.

2. RESEARCH METHODOLOGY

2.1 The Used Cement

In the experiments, Portland cement (Type 42.5 N) was utilized. This specific type of cement is produced at the Zliten Cement Factory in Zliten, Libya, in accordance with the Libyan specifications outlined in document No. 340/2009. The characteristics of this cement are illustrated in (Figure 1).

Fig. 1 Sample of Portland Cement (Zliten Factory).

Table 1 and Table 2 presents the chemical and analysis on variance (anova) on mineral composition and the quality factors according to standard specification notation of Ziliten ordinary Portland cement respectively [13]. The primary ingredients of Portland cement are tricalcium silicate [$3CaO{\cdot}SiO_2$], dicalcium silicate [$2CaO{\cdot}SiO_2$], tricalcium aluminate [$3CaO{\cdot}Al_2O_3$], and tetracalcium aluminoferrate [$4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$]. These compounds are known by their abbreviations C_3S, C_2S, C_3A, and C_4AF, respectively, in the cement industry worldwide [14].

2.3 Aluminum Oxide Sample Preparation

The employed amount of aluminum oxide was taken out of the used abrasive wheels that were gathered from a nearby metalworking company; the different kinds of abrasive wheels are depicted in Figure (2).

Table 1 Portland Cement Chemical Contents [13].

Content	Percent, Max
Loss on Organic (LOG)	1.79±0.21
Sulfur Trioxide (SO_3)	2.45±0.22
Silicon Dioxide (SiO_2)	21.66±0.28
Aluminum Oxid (Al_2O_3)	5.30±0.18
Iron Oxide (Fe_2O_3)	3.41±0.10
Calcium Oxide (CaO)	62.90±0.41
Magnesium Oxide (MgO)	1.74±0.09

Table 2 Analysis on Variance (Anova) on Mineral Composition and the Quality Factors According to Standard Specification Notation of Ziliten Ordinary Portland Cement [13].

Constituent	Percentage (%)
C_3S	43.80±4.52
C_2S	28.60±4.21
C_3A	08.29±0.49
C_4AF	10.32±0.31
Alumina Models	01.56±0.07
Silica Models	02.49±0.07
Lime Saturation Factor	00.88±0.02

2.2 Mineral Water

The mineral water requirements utilized to create the hardened concrete are presented in Table 3 [15].

Table 3 Mineral Water Specifications [15].

Specification	Percent, Max
Sodium (Na)	52.200 %
Calcium (Ca)	04.008 %
Magnesium (Mg)	02.400 %
Bicarbonates (HCO_3)	24.400 %
Chlorides (Cl)	12.270 %
Sulfur (S)	09.500 %
Total Dissolved Salts (TDS)	100 ppm
pH	7.30

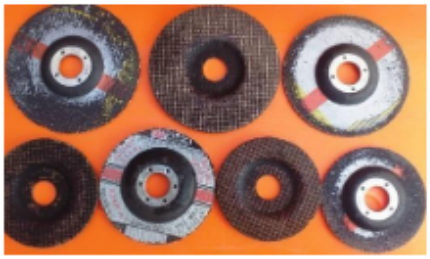

Fig. 2 Used Abrasive Wheels.

The abrasive wheels depicted in Figure 2.2 were cut into small pieces and subsequently ground to obtain powdered aluminum oxide. This powdered aluminum oxide was then mixed with a fiberglass mesh material, as illustrated in Figures (3a) and (3b).

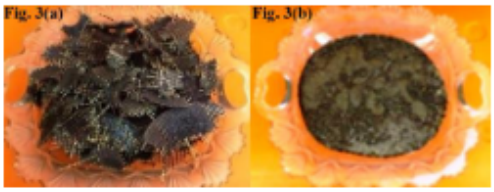

Fig. 3(a) Small Pieces of Abrasive Wheel Material, 3(b) Extracted Aluminum Oxide Powder.

To achieve maximum purification of the powdered aluminum oxide, a specific quantity as shown in (Figure 2.4) was subjected to screening using a mesh screen as shown in (Figure 4a). The screened aluminum oxide was then washed with fresh water, followed by drying using a hair dryer (as depicted in (Figure 4b). Finally, the dried aluminum oxide was balanced using an electronic balance device as shown in (Figure 4c). The initial quantity of the aluminum oxide before the purification process is illustrated

in (Figure 4d). Although the size of the aluminum oxide grains was not tested, they were generally between 0.1 and 100 microns in size since a 0.1 mm sieve was used for the final sifting of the oxide.

Fig. 4a, b, c and d Screen Mesh, Dryer, Electronic Balance Device and the Fresh Quantity of Al_2O_3.

2.4 Cement Mortar Samples Preparations

Designing the concrete with the target strength of 1560 KN in 14 days was made easier by completing all tests on the components of cement mortar and making sure that all elements, including water, sand, and cement, met ASTM specifications. The job mix was designed according to Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete (ACI 211.1-91) Reported by ACI Committee 211 [16].

The design criteria utilized in the present study are as follows: (i) Compressive strength: Cement mortar with a compressive strength of 30 MPa was employed. (ii) Water/cement ratio: The water-to-cement ratio in the job mix was set at 0.50. (iii) The actual cement mortar samples' diameter, height, area, failure load, resistance weight, and density for the job mix are listed in Table (3). The procedure for measuring the diameter of cement mortar samples A1 and B1 is illustrated in Figure 5a and 5b, respectively.

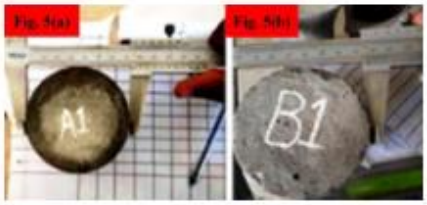

Fig. 5 a and b Procedure of Diameter Measurement of Cement Mortar Sample.

Following the evaluation of the compressive strength of plain cement mortar mix (without aluminum oxide) at 14 days of age, aluminum oxide material was incorporated into the normal cement mortar mixture at various percentages. The specific percentages of aluminum oxide, as well as the constituent materials (Al_2O_3, cement, sand, and water) used to prepare the cement mortar mix, are detailed in (Table 4).

The weights of the main constituents of cement mortar are also provided in the table. Figure 6 depicts the balancing activities conducted for the cement, sand, and water used in the experimental work. Furthermore, Figure 7 showcases the cement mortar samples after being cast in PVC casing, while Figure 8 illustrates the cement mortar samples after being removed from the PVC casing.

Fig. 6 Balancing of Cement, Sand, and Water Used in the Present Work Experiments.

2.5. Mixing, Casting and Curing Procedures

During the mixing procedure, the aluminum oxide powder was added to a mixture comprising cement, fine aggregate (sand), and water. The entire quantity was thoroughly mixed to ensure the homogeneous distribution of the aluminum oxide particles within the cement matrix. For each of the considered concentrations of aluminum oxide (0%, 1%, 2%, 3%, 4%, 5%, and 10%), three samples were produced to obtain the average compression strength. These three samples for each concentration are labeled as (A, B, C, D, E, F, and G) and are depicted in Figure (2.10). In the casting process, the fresh cement mortar was poured into PVC molds with dimensions of 76.2 mm (diameter) and 80.0 mm (length). The dimensions of the PVC molds were chosen accordance to the comparison of conversion factors for various types of cubic and cylindrical samples according to various authors and standards (Stawiski) [17]. The curing procedure involved initially allowing the hardened cement mortar to cure in the open air for 24 hours. Careful removal of the hardened cement mortar from the molds was carried out to prevent any defects in the samples. Subsequently, the samples were placed in fresh, salt-free water at a temperature of 20-27 ^{5}C for a duration of two weeks (14 days). Figure 9 illustrates the hardened cement mortar samples during the curing process in fresh water. Finally, each cement mortar sample was balanced using an electronic balance device, as shown in (Figure 10).

Table 4 Cement Mortar Sample Specification.

Sample Code	Al_2O_3 (%)	Constitutes Material (g)				Sample Weight (g)
		Al_2O_3	Cement	Sand	Water	
A1	00.0	000.00	932.131	1864.262	466.066	781
A2	00.0	000.00	932.131	1864.262	466.066	792
A3	00.0	000.00	932.131	1864.262	466.066	786
B1	01.0	093.21	922.810	1864.262	461.405	775
B2	01.0	093.21	922.810	1864.262	461.405	764
B3	01.0	093.21	922.810	1864.262	461.405	775
C1	02.0	186.43	913.488	1864.262	456.744	797
C2	02.0	186.43	913.488	1864.262	456.744	769
C3	02.0	186.43	913.488	1864.262	456.744	792
D1	03.0	279.64	904.167	1864.262	452.084	783
D2	03.0	279.64	904.167	1864.262	452.084	786
D3	03.0	279.64	904.167	1864.262	452.084	793
E1	04.0	372.85	894.846	1864.262	447.423	809
E2	04.0	372.85	894.846	1864.262	447.423	797
E3	04.0	372.85	894.846	1864.262	447.423	814
F1	05.0	466.07	885.524	1864.262	442.762	788
F2	05.0	466.07	885.524	1864.262	442.762	791
F3	05.0	466.070	885.524	1864.262	442.762	788
G1	10.0	932.310	836.918	1864.262	419.459	802
G2	10.0	932.310	836.918	1864.262	419.459	806
G3	10.0	932.310	836.918	1864.262	419.459	805

Fig. 7 Cement Mortar Samples under Curing Process.

Fig. 8 Cement Mortar Samples After Removed from PVC Casing.

Fig, 9 Immersing of Cement Mortar Samples in Fresh Water for 14 Days.

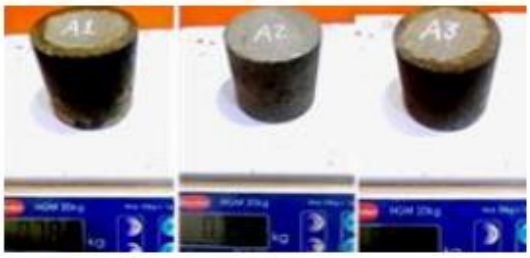

Fig. 10 Balancing of Cement Mortar Sample After 14 Days of Curing Time.

3. RESULT AND DISSECTION

Table 5 displays the sample diameter, height, and area together with the actual data for hardened cement mortar.

Table 5 Actual Data of Cement Mortar Samples.

Code	Diameter (mm)	Length (mm)	Area (mm^2)
A1	75.83	79.33	4516.19
A2	75.50	80.83	4476.96
A3	75.67	80.67	4497.15
B1	76.58	80.00	4605.96
B2	76.25	79.67	4566.35
B3	75.91	80.33	4525.72
C1	76.08	84.00	4546.01
C2	76.25	81.50	4566.35
C3	75.42	85.00	4467.48
D1	75.33	82.67	4456.83
D2	75.33	82.00	4456.83
D3	76.00	84.00	4536.46
E1	75.40	82.00	4465.11
E2	76.33	80.67	4575.94
E3	76.33	81.17	4575.94
F1	75.33	80.67	4456.83
F2	75.42	81.83	4467.48
F3	76.00	80.50	4536.46
G1	75.75	82.67	4506.66
G2	76.18	82.67	4557.97
G3	76.67	82.67	4616.80

The Uniaxial Compressive Strength tests for the hardened cement mortar were carried out in accordance with ISRM recommended procedures [18]. It was conducted using the (ELE International Machine Model) with a load speed of 100 Newton per second, as depicted in (Figure 11). Prior to testing, each sample was ground using emery paper to ensure a smooth and balanced surface, thus enabling accurate results. During the compression test, no cushioning material was inserted between the sample and the machine plates. The load was applied axially without any sudden shocks until the sample was crushed. The average failure load results for different proportions of aluminum oxide are presented in Tables (6). The results are expressed in kilonewtons (kN).

Fig. 11 (ELE In) International Compression Test Machine) Used in the Present Work.

Based on the obtained data, the failure stresses (in MPa) for each sample were determined. Additionally, the percentage increase in failure stresses was calculated. Figure 12 displays some of the hardened cement mortar samples from the present study that experienced failure under compression load.

Fig. 12 Some Hardened Cement Mortar Samples Under Compression Load Failure.

The compressive strength (σc) was calculated using the formula: σc = F/A [18], where F represents the failure load recorded by the machine after the cement mortar sample experienced failure, and A denotes the cross-sectional area of the hardened sample. The results of the compressive strength tests for cement mortar samples without the incorporation of aluminum oxide were as follows: the control sample exhibited a compressive strength of 26.61 MPa. By replacing 1.0% of the cement with aluminum oxide, the compressive strength decreased to 23.10 MPa, representing a decrease of approximately 13% compared to the control sample. Increasing the replacement of cement with aluminum oxide to 2.0% further reduced the compressive strength to 17.46 MPa, resulting in a decrease of approximately 34% compared to the control sample. Similarly, replacing the cement with 3.0% aluminum oxide led to a compressive strength of 10.87 MPa, representing a significant decrease of approximately 59% compared to the control sample. When replacing the cement with 4.0%, 5.0%, and 10.0% aluminum oxide, the compressive strengths were recorded as 12.81 MPa, 15.31 MPa, and 14.93 MPa, respectively. The decrease in compressive strength compared to the control sample was approximately 42%, 55.0%, and about 44.0% for these respective cases.

When 3% weight of Portland cement was substituted with aluminum oxide powder, the cement mortar's compressive strength dropped by as much as 59%, while the least amount of cement mortar shrinkage was 13% when 1% weight of Portland cement was substituted with aluminum oxide powder. Table 6's results make it evident that when the amount of aluminum oxide powder is increased, the compressive strength steadily decreases.

Table 6 The Results of Compression Test.

Code	Al_2O_3 (%)	F. L. (kN)	C. S. (MPa)	C. S. A. (MPa)	C. S. D (%)
A1	00.0	156.80	34.72		
A2	00.0	128.10	28.61	26.61	00.00
A3	00.0	074.20	16.50		
B1	01.0	114.20	24.79		
B2	01.0	101.30	22.18	23.10	13.19
B3	01.0	101.10	22.34		
C1	02.0	078.60	17.29		
C2	02.0	073.10	16.00	17.46	34.38
C3	02.0	085.30	19.09		
D1	03.0	024.30	05.45		
D2	03.0	052.00	11.67	10.87	59.15
D3	03.0	070.30	15.50		
E1	04.0	022.00	04.93		
E2	04.0	076.30	16.67	12.81	42.46
E3	04.0	077.00	16.83		
F1	05.0	083.20	18.67		
F2	05.0	055.10	12.33	15.31	55.09
F3	05.0	067.80	14.94		
G1	10.0	068.40	15.18		
G2	10.0	067.50	14.81	14.93	43.89
G3	10.0	068.30	14.79		

F. L. (Failure Load), C. S. (Compressive Strength), C. S. A. (Compressive Strength Average), C. S. D. (Compressive Strength Drop).

Figure 13 illustrates the relationship between the concentration of aluminum oxide and the compressive strength of the hardened cement mortar. The results indicate that the incorporation of aluminum oxide into Portland cement has a noticeable impact on the compressive strength of the cement mortar. Generally, the addition of aluminum oxide decreases the cement mortar's ability to withstand compression loads. The instability observed in the compressive strength with the addition of aluminum oxide may be attributed to the formation of porosity within the cement mortar sample.

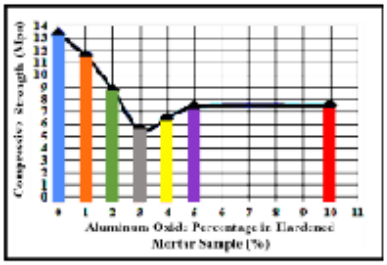

Fig. 13 Compressive Strength Vs. Aluminum Oxide Percentage Concentration.

4. RESULTS COMPARSION

Comparing to the study conducted by L. Moutei in 2018 [4], the study demonstrated that the compressive strength is enhanced by the addition of 12% alumina powder. In the current study the maximum addition of alumina powder was 10%, the compressive strength in this concentration was decreased by about 44% comparing with the cement mortar sample with no alumina powder. The study found that substituting the weight amounts of aluminum oxide for Portland cement did not result in an increase in compressive strength across all sample proportions.

Comparing to the study conducted by Lam Tang Van 2019, [6], the results concluded that an increasing in the amount of aluminium powder resulted in a decrease in the compressive strength of the aerated concrete samples. However, these results support the same results obtained in this research.

5. CONCLUSIONS

In the present investigation, different concentrations of aluminum oxide (1.0%, 2.0%, 3.0%, 4.0%, 5.0%, and 10.0%) extracted from metal cutting abrasive wheels were investigated for their impact on the compressive strength of hardened cement mortar. The results indicated a decrease in the compressive strength of the hardened cement mortar samples for all concentrations of aluminum oxide compared to the control sample which without any aluminum oxide. The maximum decreases in compressive strength was observed at an aluminum oxide concentration of 3.0%, which recorded a reduction of with 59.13%.

The decreasing in compressive strength can be attributed to the formation of porosities in the cement mortar due to the increased percentage of aluminum oxide in the Ordinary Portland Cement. The typical chemical composition of Portland cement clinker indicates an aluminum oxide content of approximately 5.3±0.18%. The presence of porosities in the cement mortar has a detrimental effect on its mechanical properties, leading to a decline in its ability to withstand compression loads.

Based on the findings of this study, it can be concluded that increasing the percentage of aluminum oxide in cement mortar results in a decrease in compressive strength. It is recommended that the aluminum oxide content in the cement material should not exceed 5.78% in any case. However, it is worth noting that the presence of aluminum oxide in cement material offers certain advantages. It acts as fluxes by increasing the amount of the liquid phase, and alumina helps in producing a higher C3S content while reducing the amount of free CaO and improving the grindability of the clinker.

In summary, the addition of aluminum oxide to a cement-based matrix negatively affects its mechanical properties, specifically its compressive strength.

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